NEW MATHEMATICAL MODELS OF BIOMASS VIABILITY AND MEMBRANE FOULING IN A MEMBRANE BIOREACTOR

By

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

The optimized performance of a membrane bioreactor (MBR) for wastewater treatment depends not only on the biomass viability but also on the dynamic effects of biomass properties on membrane fouling. This research developed new conceptual mathematical models of biomass viability and fouling using biomass parameters and operational parameters of an MBR. It also presents, as outcomes, new simple and practical models for tracking biomass viability and fouling of an MBR system. The proposed models can be used to track instability in the operation of an MBR, and consequently, measures can be taken to act against instability in the oxygen uptake and for fouling control.

The proposed conceptual models include parameters such as the specific oxygen uptake rate (SOUR) of microorganisms, the soluble or colloidal chemical oxygen demand (COD) of effluent along with the mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) concentrations. The COD parameters of the models represent soluble microbial product (SMP) or bound extra-polymeric substances (bEPS) present within an MBR, offering the possibility of developing practical models with these easily measurable parameters.

The experimental study investigated the effects of biomass parameters on SOUR in a lab-scale sponge submerged MBR (SSMBR) system. Statistical analyses of experimental results indicate that bEPS, SMP, MLSS and MLVSS had significant effects on SOUR and their relative influence on SOUR was EPS>bEPS>SMP>MLVSS/MLSS. The EPS is considered as a lumped parameter of SMP and bEPS. The progressive change of SMP and bEPS within the bioreactor consistently maintained a negative exponential correlation with SOUR, and two independent models of biomass viability were developed based on

correlations among these parameters. Both the model simulations for biomass viability agreed well with experimental values of the SSMBR system.

The simplified model of membrane fouling considered cake formation on the membrane and its pore blocking as the major processes of fouling. In the model, MLSS is used as a lumped parameter to describe the cake layer formation including the biofilm whereas SMP is assumed as the key contributor to pore fouling. The combined effects of aeration and backwash on detachment of membrane foulants, and new exponential coefficients are included to better describe the exponential increase of transmembrane pressure (TMP). With practical assumptions of these major processes, the new model successfully simulated the fouling phenomena with fairly accurate predictions of the rise of TMP for the operations of two lab-scale submerged MBR systems.

List of Publications

(06 journal papers published, 02 journal papers submitted, 03 conference presentation)

Journal Publications:

1. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Chen, S.S., Nguyen N. C., Deng, L. J., Tran, T. D.C. (2014). An Assessment of the Effects of Microbial Products on the Specific Oxygen Uptake in Submerged Membrane Bioreactor. International Journal of Environmental, Earth Science and Engineering 8(2) 22-26.
2. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S. (2013). New proposed conceptual mathematical models for biomass viability and membrane fouling of membrane bioreactor. Bioresource Technology 142, 137-40**.**
3. **Zuthi, M. F. R.,** Guo, W. S., Ngo, H. H., Nghiem, L., Hai, F. I. (2013). Enhanced Biological Phosphorus Removal and its Modeling for the Activated Sludge and Membrane Bioreactor Processes. Bioresource Technology **139, 363-74.**
4. **Zuthi, M.F.R.,** Ngo, H. H., Guo, W. S., Zhang, J., Liang, S. (2013). A review towards finding a simplified approach for modelling the kinetics of the soluble microbial products (SMP) in an integrated mathematical model of membrane bioreactor (MBR). International Biodeterioration and Biodegradation 85, 466-473.
5. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Nguyen, T.T. (2013). The effects of sponges on the dissolved organic removal in a sponge submerged membrane bioreactor. World Academy of Science and Technology (WASET) 78, 44-48.
6. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S. 2012. Modelling bioprocesses and membrane fouling in membrane bioreactor (MBR): a review towards finding an integrated model framework. Bioresource Technology 122, 119-29.

7. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Nghiem, D. L., Hai, F. I. , Xia, S. Q., Zhang, Z. Q., Li, J. X. Biomass viability: identification of influencing factors and mathematical modelling in a membrane bioreactor. (Submitted to Journal of Membrane Science).
8. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Nghiem, D. L., Hai, F. I., Xia, S. Q., Zhang, Z. Q., Chen, S. S., Nguyen, C. N. New and practical mathematical model of membrane fouling in an aerobic submerged membrane bioreactor (Submitted to Water Research).

<u>Conference Presentation:</u>

1. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Chen, S.S., Nguyen N. C., Deng, L. J., Tran, T. D.C. (2014). An Assessment of the Effects of Microbial Products on the Specific Oxygen Uptake in Submerged Membrane Bioreactor. ICEBESE 2014: International Conference on Environmental, Biological and Ecological Sciences, and Engineering, 13-14 February, 2014, Kualalumpur, Malaysia.
2. Z**uthi, M. F. R.,** Ngo, H. H., Guo, W. S., Nguyen, T.T. 2013. The effects of sponges on the dissolved organic removal in a sponge submerged membrane bioreactor. ICEBESE 2013: International Conference on Environmental, Biological and Ecological Sciences, and Engineering, 5-6 June, 2013, New York, USA.
3. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., 2012. A simplied approach for modelling the formation and degradation of soluble microbial products (SMP) in an integrated mathematical model of MBR. CESE 2012: the fifth annual conference on the challenges in environmental science and engineering, 9-13 September, 2012, Melbourne, Australia.

Table of Contents

List of Tables

List of Figures

List of Notations and Abbreviations

A. List of notations

ΔP	Pressure gradient (transmembrane pressure)
μ	Permeate (or effluent) viscosity
μ_{20}	Permeate viscosity at 20^0C
μ_{aut}	Maximum growth rate of autotrophs
μ_{het}	Maximum growth rate of heterotrophs
μ_{SMP}	maximum growth rate of SMP
μ_T	Permeate viscosity at T^0C
a	Threshold pore area
Å	Angstrom
A_m (or A)	Membrane surface area
A_t	Total pore area
B	First-order endogenous decay rate coefficient
bE_i/bE_0	$bEPS_i/bEPS_0$
b_H	Endogenous respiration rate
C	Sludge concentration
C_0	Inert COD in the influent
C_d	Coefficient of the lifting force of a sludge particle
C_m (or C_b)	Concentration of fouling particles
C_m^b	Concentration of particles entering the membrane pore
$COD_{c,eff}$	Colloidal COD in the effluent
COD_i	Total inert COD in the influent
COD_{perm}	COD in the permeate (effluent)
$COD_{s,eff}$	Soluble COD in the effluent
C_s	Inert COD in the effluent
C_{SMP}	Concentration of soluble particles entering the pores
$d_{f,o}$ (or $m_{d,o}$)	Membrane outer diameter
$d_{i,o}$ (or $m_{d,i}$)	Membrane inner diameter
d_p	Sludge particle diameter

D_s	Pore area fractal dimension
E_i/E_o	EPS_i/EPS_0
f	Membrane porosity
f_b	Fraction of biomass that ends up as microbial products
f_{bap}	Fraction of BAP produced during cell lysis
f_{BAP}	BAP fraction below critical molecular weight
f_{EPS}	growth associated EPS formation coefficient
$f_{EPS,d}$	non-growth associated EPS formation coefficient
f_s	fraction of suspended solids produced from EPS hydrolysis/dissolution
f_{UAP}	UAP fraction below critical molecular weight
G	Geometry factor for fluid flow through a pore
h_m	Membrane effective thickness
I	Fouling potential index
J	Flux (of flow)
J^*	Normalized flux
J_s^*	Normalized specific flux
J_{so}	Specific flux at time zero
J_t	Total flux
K	constant
$K_{1,}$	UAP formation rate coefficient
K_2	BAP formation rate coefficient
K_{bap}	Half saturation coefficient for BAP
K_{eps}	EPS formation coefficient
$K_{h,bap}$	Hydrolysis rate of BAP
$K_{h,EPS}$	Rate of EPS hydrolysis/dissolution
k_{hyd}	First-order hydrolysis rate coefficient
K_La_{20}	Oxygen transfer parameter
k_{MP}	Half saturation coefficient for microbial products
K_{SMP}	SMP half saturation coefficient for heterotrophs
k_α	An empirical parameter
L_0	Constant

L_b	Biofilm thickness
M_1/M_2	MLVSS/MLSS
$MLSS_{sludge}$	MLSS of sludge
M_{sc}	Mass of biomass accumulated on the membrane surface
N	Nitrogen
N_2O	Nitrous oxide
NaOCl	Sodium hypochlorite
n_c	Exponential coefficient for cake layer resistance
NH_4-N	Ammonia nitrogen
NO_2-N	Nitrite-N
NO_3-N	Nitrate- N
n_p	Exponential coefficient for pore fouling resistance
P	Phosphorus
PACl	Poly-aluminium chloride
PO_4-P	Phosphate P
Q	Flow rate
R^2	Squared value of correlation coefficient
$R_{biofilm}$ (or R_b)	Resistance due to biofilm
r_c	Specific cake resistance
$R_c(z)$	Time-dependant cake layer resistance
R_{cake}	Resistance due to cake formation
R_m	Membrane intrinsic resistance
R_p	Pore fouling resistance
r_p	Specific resistance of pore fouling
r_p	Membrane pore radius
r_p	Pearson correlation coefficient
$R_p(z)$	Time-dependant pore blocking resistance
R_{sc}	Stable sludge film resistance
r_{sc}	Specific resistance of stable sludge film
R_{sf}	Dynamic sludge film resistance
r_{sf}	Specific resistance of dynamic sludge film

R_T	Total resistance
R_{Tot}	Total membrane resistance
S_{BAP}	BAP (COD units)
$sBOD_5$	Soluble 5-day biological oxygen demand
sCOD	Soluble COD
S_i	Influent substrate concentration
$SMP_{cake\text{-}mem}$	SMP concentrations in cake layer-membrane interface
$SMP_{permeate}$	SMP concentrations in the permeate
$SMP_{reactor}$	SMP concentration within the bioreactor
S_{ND}	Soluble biodegradable organic nitrogen
S_{NH}	Ammonia or ammonium nitrogen
SP_i/SP_0	SMP_i/SMP_0
S_{PO4}	Soluble phosphate
S_S	Readily biodegradable substrate
S_{UAP}	UAP (COD units)
t	Filtration period
t_f	Elapsed filtration time
u_b	Biofilm detachment rate during backwashing
$u_{f,a}$	EPS growth rate due to attachment
$u_{f,d}$	EPS growth rate due to detachment
U_{Lr}	Crossflow velocity of tap water
U_{sr}	Crossflow velocity of mixed liquor
V	Volume of permeate passed through the available membrane area
V_f	Water production within the filtration period of the operation cycle
V_f	Permeate volume after time t_f
V_s	Cumulative volume of permeate per membrane surface area
X	Biomass concentration
X_A	Active autotrophic biomass
X_{aut}	Autotrophic Biomass Concentration
X_{EPS}	EPS concentration
X_{GLY}	Stored glycogen in PAOs
X_{het}	Heterotrophic biomass concentration

List of notations

X_{ND}	Particulate biodegradable organic nitrogen
X_P	Particulates from biomass decay
X_S	Slowly biodegradable substrate
Y_{BAP}	BAP formation constant
Y_{H2}	anoxic growth yield coefficient
Y_{MP}	Yield coefficient for growth on microbial products
z_c	Depth of cake layer
α	Stickiness of biomass particles
α_b	Specific resistance of biofilm
α_f	Membrane porosity reduction coefficient
α-factor	Oxygen transfer rate
α_{max}	An empirical parameter
α_o	An empirical parameter
α_p	An empirical parameter
α_v	Air scouring coefficient
β	Erosion rate coefficient of the dynamic sludge
β	Soluble Fouling Index (MFI) coefficient
γ	A coefficient for dynamic sludge compression
γ	Suspended solids MFI coefficient
$\gamma_{MP,A}$	Autotrophic microbial product formation constant
$\gamma_{MP,H}$	Heterotrophic microbial product formation constant
η	Viscosity of the permeate
η_f	Average fraction of soluble particles that accumulate in the pores
θ	Pore tortuosity
θ_f	Filtration period
v_{air}	Scouring air surface velocity
ρ_b	Biofilm density
ρ_c	Density of cake layer
ρ_p	Particle density

B. List of abbreviations

AOB	Ammonia-oxidizing bacteria
APHA	American public health association
ASMs	Activated sludge models
BAPs	Biomass associated products
BEPR	Biological excess phosphorus removal
bEPS	Bound extracellular polymeric substances
BF-MBR	Hybrid biofilm MBR
bio-P	Biological phosphorus
BNRS	Biological nutrient removal system
BOD	Biological oxygen demand
BPC	Biopolymeric clusters
C/N	Carbon to Nitrogen
C/P	Carbon to Phosphorus
CAS	Conventional activated sludge
CH	Carbohydrate
CIFI	Chemical-irreversible FI
CMBR	Conventional MBR
COD	Chemical oxygen demand
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
EBPR	Enhanced biological phosphorus removal
ED	Electrodialysis
EMBRs	Extractive MBRs
EPS	Extracellular polymeric substances
F/M	Food to microorganisms ratio
FACASM1	Fully Coupled ASM1
FI	Fouling index
FS	Flat sheet
GAOs	Glycogen accumulating organisms
HF	Hollow fibre

HIFI	Hydraulic-irreversible FI
HRFI	Reversible FI by hydraulic backwash
HRT	Hydraulic retention time
IC	Inorganic carbon
IUPAC	International union of pure and applied chemistry (IUPAC)
IWA	International water association
LC-OCD	Liquid chromatography- organic carbon detection
MABRs	Membrane-aerated biofilm reactors
MBBR	Moving bed biofilm reactors
MBR	Membrane bioreactor
MF	Microfiltration
$MFI_{0.45}$	Modified fouling index
MFI_{MBR}	MFI of MBR
MFI_{sol}	MFI of soluble particles
MFI_{SS}	MFI of suspended particles
MLSS	Mixed liquor suspended solid
MLVSS	Mixed liquor volatile suspended solids
MT	Mutitube
NF	Nanofiltration
NFFB	Non-oven fabric filter bag
OHs	Ordinary heterotrophic organisms
OLR	Organic loading rate
OUR	Oxygen uptake rate
P	Phosphorus
PAC	Powdered activated carbon
PAOs	Phosphorus accumulating organisms
PFC	Polymeric ferric chloride
PHA	Polyhydroxyalkanoates
PN	Protein
poly-P	Polyphosphate
PS	Polysaccharide

PUS	Polyster-urethane sponge
PVDF	Polyvinylidene fluoride
R	Resistance
RBCOD	Readily biodegradable COD
RO	Reverse osmosis
SBNR	Shortcut biological nitrogen removal
$sBOD_5$	Soluble 5-day biological oxygen demand
SCOD	Slowly biodegradable COD
SDI	Silt density index
SEM	Scanning electron micrographs
sEPS	Soluble EPS
SMBR	Submerged MBR
SMBR	Submerged membrane bioreactor
SMP	Soluble microbial products
SOUR	Specific oxygen uptake rate
SRT	Sludge retention time
SS	Suspended solids
SSMBR	Sponge submerged MBR
SSMBR	Sponge submerged MBR
T	Temperature
TC	Total carbon
TEP	Transparent exopolymeric particles
TFI	Total FI
TKN	Total kjeldahl nitrogen
TMP	Transmembrane pressure
TOC	Total organic carbon
TSS	Total suspended solids
TUDP	Technical university of Delf phosphorus
UAPs	Utilization associated products
UCT	University of Cape Town
UCTPHO	UCT phosphorus

UF	Ultrafiltration
UMFI	Unified FI
UTS	University of Technology Sydney
UV	Utlraviolet
VSS	Volatile suspended solids